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Giant Dipole Resonance in the hot and thermalized ^{132}Ce nucleus: damping of collective modes at finite temperature

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The γ decay of the Giant Dipole Resonance in the ^{132}Ce compound nucleus with temperature up to $\approx$ 4 MeV has been measured. The symmetric ^{64}Ni + ^{68}Zn at E_{beam} = 300, 400, 500 MeV and the asymmetric reaction ^{16}O + ^{116}Sn at E_{beam} = 130, 250 MeV have been investigated. Light charged particles and γ rays have been detected in coincidence with the recoiling compound system. In the case of the mass symmetric ^{64}Ni induced reaction the γ and charged particle spectral shapes are found to be consistent with the emission from a fully equilibrated compound nuclei and the GDR parameters are extracted from the data using a statistical model analysis. The GDR width is found to increase almost linear with temperature. This increase is rather well reproduced within a model which includes both the thermal fluctuation of the nuclear shape and the lifetime of the compound nucleus.

The study of the properties of the Giant Dipole Resonance (GDR) at high temperature and angular momentum is one of the central topic in nuclear structure as it provides an insight into the behaviour of nuclei under extreme conditions. The wealth of experimental data on this subjetct covers mainly an interval of temperature up to $\approx$ 2.5 MeV and is mainly based on the study of the γ decay from fusion-evaporation reactions. These data have been shown to provide an important testing ground for the theoretical models. In particular, the change of the GDR width with angular momentum and temperature reflects the role played by quantal and thermal fluctuations in the damping of the giant vibrations [1–7]. While, in general, the experimental results at T < 2 MeV are rather well understood within the thermal fluctuation model (TFM), at temperature higher than 2.0 MeV the situation is more complex. In fact, the most recent works [8, 9] have raised the very important question on whether or not the thermalization process at the highest excitation energies is properly known and, consequently, if the temperature of the γ ray emitting systems can be determined correctly. This very relevant remark was pointed out and discussed in connection with the measurements of γ rays and light charged particles (LCP) in Sn isotopes at temperature up to $\approx$ 2.5 MeV using the reaction ^{18}O + ^{100}Mo with E_{beam} = 122-217 MeV. The analysis of the LCP spectra has shown that the pre-equilibrium contribution is sizable, corresponding, in the case of the highest bombarding energies, to a loss of excitation energy of up to 20 %. Another very interesting aspect of the work of M.P.Kelly *et al.* [8, 9] concerns the reinterpretation of the previous GDR experiments made by other groups at T > 2.0 MeV using different projectile and target combinations [8–14]. This reinterpretation was motivated by the effort of a better definition of initial excitation energy of the decaying nuclei which can, in fact, strongly affect the results on the GDR width. Indeed the analysis of M.P.Kelly and collaborators on the existing data brought to a variation of the original picture where a saturation of the GDR width was previously observed. A continuous increase of the GDR width with the temperature resulted [8] indeed when the values of the excitation energies were corrected for the pre-equilibrium emission using the best predictions for fusion reactions. It is clear from the above considerations that the problem of the behaviour of the GDR at the highest temperature (T > 2.0 MeV) is presently an open question.

In order to improve the experimental picture concerning the problem of the damping of collective modes as obtained from the γ decay of the GDR at high excitation energy one needs to use reactions in which the pre-equilibrium contribution is minimized and the excitation energy is deduced and confirmed from LCP spectra. The present work reports on an experiment concerning the GDR in the mass A $\approx$ 130 region at an average temperature in the interval T= 2-4 MeV using the symmetric reaction ^{64}Ni + ^{68}Zn leading to ^{132}Ce. The used bombarding energies of 300, 400 and 500 MeV correspond to the kinematical value of excitation energy E^* = 100, 150 and 200 MeV. In the experiment LCP, γ rays and the heavy recoiling nuclei have been measured in coincidence. In addition we measured with the same experimental conditions the LCP, γ rays and heavy recoiling nuclei produced in the asymmetric mass entrance channel reaction ^{16}O + ^{116}Sn, which should lead to the same compound ^{132}Ce at $E^* = 100$ and 200 MeV, as deduced from kinematics. This last reaction was used to define and compare the pre-equilibrium contribution, which was predicted in a similar case by M.P.Kelly *et al.* The experimental conditions have been chosen in order to add information to the picture of the GDR width in the high excitation energy regime, studying a mass region very similar (spherical ground state) to that of the Sn isotopes, where a continuous increase of the width with the temperature was observed after the excitation energy correction.

The present experiment was performed at the Legnaro National Laboratory of INFN using a set up consisting of the GARFIELD array [15] combined with the large volume BaF_2 detectors of the HECTOR set up [16] and two Position Sensitive Parallel Plate Avalanche Counter telescopes (PSPPAC)[15]. The GARFIELD array measured light charged particles and fragments. It consists of a large drift chamber, divided into 24 sectors. Each sector is then subdivided in 4 pseudo-telescopes formed by ΔE gas microstrip detectors coupled to CsI(Tl) crystals. The detection and identification of light charged particles and fragments emitted between 30^o to 85^o was possible through the combined use of the ΔE-E and drift time signals. HECTOR consists of 8 large (14.5 x 17 cm) BaF_2 scintillators for the measurement of high energy γ rays [16]. In the present experiment the detectors were placed inside the large GARFIELD scattering chamber at backward angles between 125 and 160 degree. Recoiling nuclei were measured by a PSPPAC system covering angles between 4^o and 12^o. Each PSPPAC system consists of two position sensitive PPACs with an Upilex foil between them. The thickness of the foil was chosen in order to stop only the evaporation residues and let the scattered beam or the projectile-like fragments pass through. The request of anti-coincidence between the two PSPPACs combined with the measurement of the time of flight cleanly selected only the fusion residues. The BaF_2 detectors were calibrated using standard γ rays sources and the 15.1 MeV γ rays from the reaction $d(^{11}B, n\gamma)^{12}C$ at 19.1 MeV. An electronic threshold of $\approx$ 4 MeV was applied for γ rays. The GARFIELD detectors were calibrated using elastic scattering of ^{12}C and ^{16}O from 6 to 20 MeV/A. The identification threshold for LCP and fragments was about 900 keV/A. For all the reactions the same tagging conditions from the PPACs identification of the recoiling residues were used both for the light charged particles and for the γ rays.

Spectra of the charged particles and of γ rays tagged by heavy recoiling residual nuclei were obtained by applying the same conditions on the PSPPAC time of flight data. The kinetic energy spectra of LCP have been measured at different angles. In figure 1 selected α-particle spectra measured in the present experiment are shown. In particular the value of the excitation energy deduced from kinematics is the same for the two reactions, namely for the ^{16}O + ^{116}Sn at E_{beam} = 250 MeV (top row) and for the ^{64}Ni + ^{68}Zn at E_{beam} = 500 MeV (bottom row). In the left panels the spectra measured at different center of mass angles, normalized in the region of the maximum yield, are displayed. While the α-particle spectra corresponding to the O-induced reaction show a very different spectral shape at varying angles, the spectral shape corresponding to the Ni-induced reaction is not changing with angles. This behaviour of the α-particle angular distribution for the O-induced reaction reflects the presence of a sizable pre-equilibrium contribution in the emission of the compound nucleus as deduced from the strongly forward focused α-particle yields. To verify this explanation statistical model calculations were made. The results of these calculations are shown in comparison with the data in the right panels of figure 1. The α-particle spectrum of the Ni-induced reaction is very well reproduced by the calculation implying emission from a fully thermalized compound system. In contrast, the statistical model calculations cannot describe the large extra yield measured with the O-induced reaction and a more complete analy-

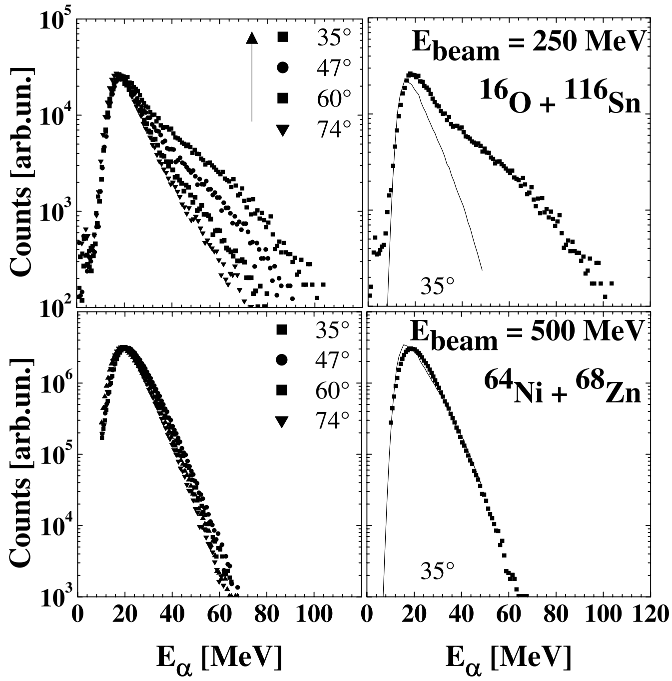

FIG. 1: Left panels: measured α-particle spectra in the CM frame system at different detection angles for the two different mass entrance channel reactions. The lower panel shows the measured yield for the Nickel-induced reaction (E_{lab}=500 MeV). The upper panel shows measured α-particle spectra for the Oxygen-induced reaction (E_{lab}=250 MeV). Right panels: measured α-particle spectra at 35^o in the CM system for the Oxygen and Nickel induced reactions. The continuous line in both right panels indicates the results of statistical model (Hauser-Feshbach evaporation) calculations [20, 21].

sis including other contributions such as that from a non equilibrated thermal source is necessary to understand the data. Therefore the study of the GDR problem in the present paper is restricted to the data obtained with the Ni-induced reaction corresponding to a symmetric mass entrance channel system. Extensive analyses of the LCP spectra for both symmetric and asymmetric reactions will be the subject of a future paper.

The γ-ray spectra measured in coincidence with the recoiling residual nuclei, from the symmetric reaction induced by Nickel, are shown in figure 2 (symbols) together with the best fitting statistical model calculations (full line). The calculation was performed using the computational code of references [22, 23]. The calculated spectra were folded with the response function of the experimental set-up calculated using the GEANT [24] libraries. The GDR parameters were extracted using a χ^2 minimization procedure. A single Lorentzian strength function centered at $E_{GDR} \approx 14$ MeV (as found also in [19]) and a value of the energy-weighted sum rule (EWSR) corresponding to ≈ 100 % were used. In order to display spectra on a linear scale to emphasize the GDR region the quantity $F(E_\gamma)Y_\gamma^{exp}(E_\gamma)/Y_\gamma^{cal}(E_\gamma)$ was plotted in the insets of figure 2. $Y_\gamma^{exp}(E_\gamma$ is the experimental spectrum and $Y_\gamma^{cal}(E_\gamma)$ the best fit calculated spectrum, corresponding to the single Lorentzian function $F(E_\gamma)$.

The resonance width and centroid were treated as free parameters of the fit. For the level density description the Reisdorf formalism of Ignatyuk [25, 26] was used, which includes small shell corrections at low energy and which is characterized by a nearly constant level density parameter a whose value is between A/9 and A/10 MeV^{-1} for the higher energy region, T > 2 MeV. Since the experimental bombarding energies imply a saturation of the angular momentum of the compound nucleus (CN) an average value of $< J > = 45\ \hbar$ and maximum of $L_{max} = 70\ \hbar$ was used for all the present calculations. The best fitting values deduced from the analysis of the GDR region correspond to a width $\Gamma_{GDR}= 8 \pm 1.5$, 12.4 ± 1.2 and 14.1 ± 1.3 MeV at $E^* = 100, 150, 200$ MeV, respectively. Note that the statistical model calculation of the α spectra at bombarding energy of 500 MeV of figure 1 (right-bottom panel) was made with the same values of the excitation energy.

The nuclear temperature of the compound nucleus associated with the GDR decay was calculated with the expression $T = 1/[dln(\rho)/dE]$, as discussed in ref [27, 28], where ρ is the level density. The resulting value for the present data is not substantially different from the value calculated using the relation $T^2 = [(E_x - E_{rot} - E_{GDR})/a)]$, where E_{rot} is the rotational energy. The average temperature for the emission of the γ ray from the GDR was calculated averaging the previous expression with the γ ray yield at transition energy between 12 to 25 MeV. The obtained average temperature corresponds to the values T =1.8, 2.8 and 3.7 MeV, respectively for

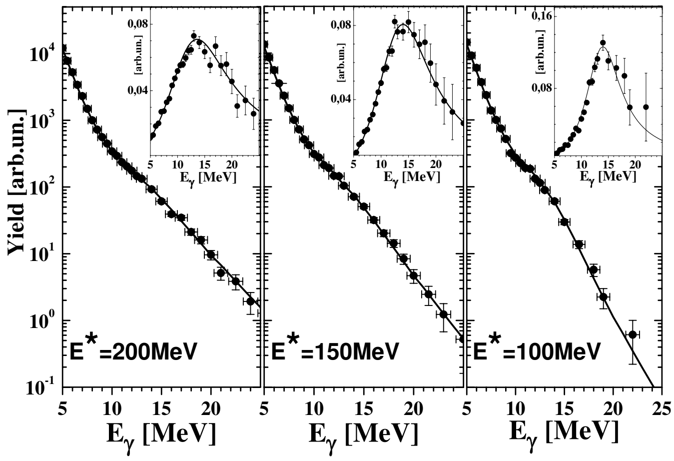

FIG. 2: The measured (filled points) and calculated statistical model (full drawn line) high energy γ-ray spectra for ^{132}Ce at 200, 150 and 100 MeV of excitation energy. The calculations have been performed assuming a fully thermalized CN and an average spin $< J >$ of 45 $\hbar$. In the insets of the figure the quantity $F(E_\gamma)Y_\gamma^{exp}(E_\gamma)/Y_\gamma^{cal}(E_\gamma)$ (see text) is plotted. The full drawn lines correspond to the best fitting single component Lorentzian functions.

E_{beam} = 300, 400 and 500 MeV. These values are approximately 0.5 MeV lower than the initial temperature of the compound nuclei.

The measured values of the GDR widths are shown in figure 3 together with the existing data at lower temperature which correspond to reactions leading to fully thermalized compound nuclei [29, 30]. The data for the Ce isotopes are also compared with different theoretical predictions based on the thermal fluctuation model of the nuclear shape. Within this model the GDR strength function is calculated by averaging the line shape corresponding to the different possible deformations. The averaging over the distribution of shapes is weighted with a Boltzmann factor $P(\beta, \gamma) \propto exp(-F(\beta, \gamma)/T)$ where F is the free energy and T the nuclear temperature [2, 31, 32]. At each deformation point the intrinsic width Γ_0 of the resonance was chosen equal to the zero temperature value, namely 4.5 MeV, as it was generally done to reproduce the existing majority of data at T < 2.5 MeV. This calculation is shown with a thin continuous line in figure 3. One can note that the predicted increase does not reproduce the present experimental data at T > 2.5 MeV. In addition the predicted increase follows rather well the deformation increase of the compound nucleus induced by temperature. This is also shown in figure 3 where the average deformation of the nucleus obtained by the thermal fluctuation model is shown with a dashed line (scale on the right vertical axis). A possible explanation for the discrepancy between the data and the standard thermal fluctuation model at T > 2.5 MeV could be related to the fact that the effect of the lifetime of the compound nucleus could play a role at these temper-

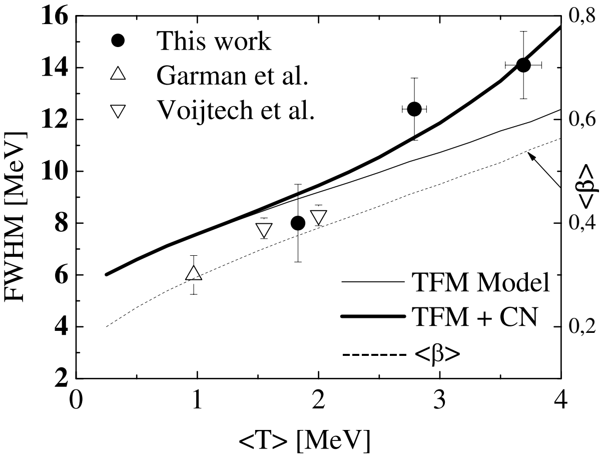

FIG. 3: Comparison between measured (black points) and calculated GDR width at $< J >= 45\hbar$. The thick continuous line shows the calculations where also the change in the compound nucleus (CN) lifetime is included in the thermal shape fluctuation simulation. The thin continuous line indicates the results where such effect is not included. The data from literature Garman *et al.* [29] (empty upwards triangles) have been measured at $< J >\approx 8\hbar$ and $16\hbar$ while those of Voijtech *et al.* [30] (empty downwords triangles) have been measured at $< J >\approx 23\hbar$ and $27\hbar$. The dashed line shows the average deformation $< \beta >$ calculated by the thermal fluctuation model [7, 32] (scale on the right axis).

atures. This question has been originally addressed by Ph.Chomaz et al. [32–35] who showed the importance of this effect at temperature larger than 3 MeV. The present calculation with the thermal fluctuation model including also the compound nucleus lifetime is shown in figure 3 with a thick full drawn line. In this case a remarkable agreement between the experimental data and the predictions is found. From the present comparison one can also note that for T > 2 MeV there is no room for a significant increase of the intrinsic width Γ_0 with temperature, unless one unrealistically neglects the CN lifetime contribution to the total width.

The picture deduced from the present experiment is consistent with that presented in the work of M.P.Kelly et al. for the Sn isotopes. The GDR width does not saturate at T > 2.5 MeV but increases steadily with temperature at least up to 4 MeV. However, in the Sn work the data were corrected for the pre-equilibrium emission at variance with the present case for which no corrections on the excitation energy were necessary and for which the excitation energy was deduced from the analysis of both LCP and γ rays measured in coincidence with heavy recoiling nuclei. The consistent behaviour of the GDR width with increasing temperature found in the two mass regions of Sn and Ce in the interval T = 2.5 -4 MeV sheds more light on the interesting problem of the damping mechanisms of collective modes at finite temperature. Deformation effects and intrinsic lifetime of the compound nucleus are the two combined mechanisms which explain the measured increase of the width with temperature. Exclusive studies of this type should be therefore pursued also in other mass regions including more exotic ones, or in other rotational frequency regimes to further test nuclear structure in the extreme condition of finite temperature and learn about nuclear deformation.

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[1] Giant Resonances: Nuclear Structure at Finite Temperature, P.F.Bortignon, A.Bracco and R.A.Broglia, Contemporary Concepts in Physics, Harwood Academic Publishers, Amsterdam (1998)
[2] D.Kusnezov and E. Ormand, Phys. Rev. Lett. 90 (2003) 042501-1 ref. therein
[3] F.Camera *et al.* Nucl Phys. A572(1994)401
[4] M.Matiuzzi *et al.* Phys. Lett. B364(1995)13
[5] P.F.Bortignon *et al.* Phys. Rev. Lett. 67, (1991) 3360
[6] J.H.Le Faou *et al.* Phys. Rev. Lett. 72, (1994) 3321
[7] M.Gallardo *et al.*, Nucl. Phys. A443, 415 (1985)
[8] M.P.Kelly *et al.* Phys. Rev. Lett. 82(1999)3404
[9] M.P.Kelly *et al.* Phys. Rev. C56(1997)3201
[10] D.R.Chakrabarty *et al.* Phys. Rev. C36(1987)1886
[11] A.Bracco *et al.* Phys. Rev. Lett. 62(1989)2080
[12] R.J.Voijtech *et al.* Phys. Rev. C 40(1989)R2441
[13] G.Enders *et al.* Phys. Rev.Lett. 69(1992)249
[14] H.J.Hoffman *et al.* Nucl. Phys. A571(1994)301
[15] F.Gramegna *et al.* Nucl. Inst. Meth. A389(1997)474
[16] M.Kmiecik *et al.* Phys. Rev. C70(2004)064317 ref. therein
[17] O.Wieland *et al.* Work in progress (to be published)
[18] V.L. Kravchuk *et al.* IWM 2006 confernce proceeding and S. Barlini *et al.* to be published
[19] D.Pierroutsakou *et al.* Eur.Phys. J A 17(2003)71
[20] A.Gavron, Phys. Rev. C 20, 230 (1980)
[21] I.M.Govil *et al.*, Phys. Lett. B197(1987)515
[22] F.Pulhofer Nucl. Phys.A280(1977)267
[23] I.Dioszegi Phys. Rev. C 64(2001)019801 ref. therein
[24] R.Brun *et al.*., CERN Report No.CERN-DD/EE/84-1,
[25] W.Reisdorf, Z.Phys. A300(1981)227 and A.V.Ignatyuk *et al.* Sov. J. Phys. 21(1975)255
[26] I.Dioszegi *et al.* Phys.Rev. C 63(2001)047601
[27] M.Kmiecik *et al.* Nucl Phys. A674(2000)29
[28] M.Thoenessen Riken Review no 23 (july 1999)
[29] E.F.Garman *et al.* Phys.Rev. C 28(1983)2554
[30] R.K.Voijtech *et al.* Phys.Rev C 40(1989)2441
[31] W.E.Ormand *et al.* Nuc. Phys. A617(1997)20
[32] W.E.Ormand *et al.* Nucl. Phys. A614, 2(1997)217.
[33] Ph.Chomaz, Phys. Lett. B347(1995)1
[34] Ph.Chomaz, Nucl. Phys. A569(1994)569
[35] A.Bracco *et al.* Phys Rev. Lett. 74(1995)3748